

Development and Experience of a Practical, Pressure-Tolerant, Lithium Battery for Underwater Use

Dr Richard A Wilson, Bluefin Robotics Corporation, 237 Putnam Avenue, Cambridge, MA 02139 USA[†]
Dr James W. Bales, MIT Edgerton Center, Room 4-406, 77 Massachusetts Avenue, Cambridge, MA 02139 USA

Abstract—For a number of years, lithium-ion batteries have promised energy and power densities that make them an attractive alternative to the silver-zinc batteries historically used in underwater vehicles. For AUV (Autonomous Underwater Vehicle) application, polymer-electrolyte cells offer the promise of pressure tolerance; this key attribute impacts vehicle design and operational logistics in a number of ways. Primarily, it facilitates the design of arbitrarily large battery packs by obviating many of the problems associated with large, heavy and expensive pressure vessels that would have been otherwise required to house batteries at depth. This allows a single AUV operator to recover the vehicle and remove and replace the batteries in minutes without the down time associated with servicing o-rings and seals. In a military context, this new operational paradigm has made back to back search and classify missions a practical reality. As with all new technologies there is a hiatus between availability, practical implementation and adoption. Many fundamental, logistical and practical engineering problems in design and manufacture have been solved in the past 5 years leading to a range of commercially available batteries with power densities exceeding 100Wh per neutrally buoyant Kg. This paper will explore these challenges, examining specific solutions derived from experience gained through the pressure testing of over 20,000 cells.

I. INTRODUCTION

Batteries for deep sea systems have been operated at ambient pressure for many decades [1-6]. Traditionally, these batteries have employed liquid-electrolyte cells (lead-acid or silver-zinc) with inert oil floating on the electrolyte as a pressure-compensating fluid. This pressure compensated approach removes the need for heavy pressure vessels and increases the buoyancy by an amount equal to the weight of the water displaced by the cells themselves. Early pressure-compensated batteries were not without their problems. For example, if the batteries were tipped, the compensating oil could flow across the plates displacing the electrolyte thereby reducing battery capacity.

A battery that employs a solid electrolyte, and is fabricated with no void spaces, can be readily made pressure tolerant, either through packaging in a compensating fluid, encapsulation in (e.g.) a urethane, or both. Lithium-ion secondary cells using a polymer-electrolyte (Li-poly cells) came into production in the 1990s. Bluefin engineers recognized that this technology could be employed as the base building block cell for such a battery for AUVs and other undersea platforms.



Figure 1. Bluefin pressure tolerant 1.5kWh battery with ‘Drop and Play’ connector system.

In 1999 Bluefin Robotics was awarded SBIR funding to develop a smart, high-performance, pressure-tolerant battery using Li-poly cells. Since then, many fundamental, logistical and practical engineering problems in design and manufacture have been solved, leading to a range of commercially available batteries with power densities exceeding 100Wh per neutrally buoyant Kg.

The path to a commercially-viable pressure-tolerant battery (Figure 1) proved to be longer and far more arduous than was originally expected, and the level of effort required has significantly exceeded that of the original two-phased SBIR program. We start with an overview of the mature pressure-tolerant battery currently in production. Then we provide a detailed description of Bluefin’s COTS, pressure-tolerant battery for AUVs, followed by a summary of the manufacturing process. Next we discuss the engineering challenges, examine specific solutions, and describe some of the lessons learned over the course of pressure testing over 20,000 cells. We pay particular attention to the major drivers of operator and vehicle safety, ease of handling and logistics, and reliability. We close with a summary of the effort required to create a new pressure tolerant battery.

II. BATTERY OVERVIEW

A. *Quanta and Bricks*

The fundamental units of a Bluefin battery are the *quanta*, groups of 8, 16 or 20 cells permanently wired together in parallel to increase capacity. The initial encapsulation occurs

[†] Please address correspondence to Dr. Wilson.

at the level of the quanta. Quanta are then connected in parallel to form *bricks*, with bricks connected in series to form the battery.

B. Integrated control and safety electronics

Integrated into each battery is a printed circuit board bearing an embedded microcontroller, sensors, MOSFET switches, fuses, and low-level battery safety electronics. The controller can switch the battery on or off (via the MOSFETs) upon external command, or when various criteria are met. The microcontroller monitors the discharge rate of the battery and tracks the remaining capacity. It also acts as the charge controller, ensuring that the cells are charged quickly, but safely, and according to the manufacturer's specifications. The metal lid to the battery acts as a heat sink for the electronics

C. Mechanical

Mechanically, the quanta and bricks are themselves located in the same the oil-filled volume occupied by the control electronics. The pressure compensator is an integral part of the battery housing. It does not protrude beyond the batteries footprint and has minimal maintenance requirements. Once sealed, the battery is ready for inserting in to an AUV where buoyancy foam is added as required.

D. Balancing cells

As with any secondary cell, Li-polymer cells can be damaged through overcharging or overdischarging. They can undergo a violent thermal runaway if they become too hot. And, when Li-polymer cells are connected in series it is vital that the cells be kept in balance to increase the available capacity and to avoid the situation where one cell/quanta/brick exceeds safe voltage limits. That is, when charging or discharging, all cells connected together in series must move through the same charge state in synchrony. The key to keeping the cells balanced is the internal micro-controller that controls the balance resistors. These are used to divert charge current around high voltage bricks during charging or (secondarily) to dissipate energy from multiple high bricks. Balancing is normally invisible to the user, taking place during charging. Occasionally, a longer balance is required that dissipates energy from the highest voltage bricks.

The AUV operator is free to delay (secondary) balancing of the cells (with the risk of reduced capacity) until it fits the users operational cycle. Once time permits, the operator instructs the microcontroller to balance the battery as part of the standard charging and maintenance cycle. Crucially, the internal micro-controller prevents the balance mechanism from over discharging cells due to user error.

III. THE MATURE DESIGN

The mature design for Bluefin's pressure-tolerant battery has several design features that maximize its utility for AUVs (Figure 1). Electrically, the battery provides 1.5 kWh of energy at 30 VDC (nominal), with a maximum discharge rate

of 30A. As discussed, a micro-controller-based electronics package integrated into each battery controls both the charge and discharge processes while also monitoring and reporting cell voltages, distributed temperatures, current, and energy. Fast acting protection mechanisms are in place that secure the battery if an out of tolerance condition occurs, and additional protection is included should the electronics fail (for instance, if the solid state 30A over-current protection fails, the output is also mechanically fused at 35A). These fuses are considered the final level of safety devices. Under all normal, and most abnormal, circumstances the microcontroller will disconnect the battery by turning off the MOSFETs before the current reaches the level that the fuse would blow.

There are other specific (AUV) features that the architecture allows. For instance, arbitrary numbers of packs can be paralleled without external diodes while the communication scheme allows all batteries to share the same RS485 communication bus.

To turn the pack on, a single pin is connected to the battery ground. When connected, this pin enables the internal board. Once disconnected, the board reduces its current to a minimum for long term storage. Once the board is enabled, the microcontroller checks a user settable flag to determine if the battery is a Master or a Slave. If the battery is a Master, the output MOSFET switches are enabled and the battery delivers energy to the battery bus. In an AUV application, the main vehicle computer comes alive and immediately checks the AUV for faults. If no faults are discovered then the computer can communicate with the remaining Slave batteries and command that they also turn on. In this way, the vehicle is protected from the damage that might ensue if all three batteries (90 Amp capable) turned on in to a full short.

Once communication has been established, the batteries automatically enter a watchdog mode where they require communication periodically to remain on. Since water entering a connector is likely to disrupt communications, this feature helps to prevent damage due to water intrusion on the pins of the penetrators to the pressure vessel, which could potentially sink a vehicle.

Collateral damage due to the failure of electronics, firmware or 'charge-ware' is potentially most serious during charge. Over charged or overheated cells can cause catastrophic damage to batteries, vehicles and infrastructure. The practical safety mechanisms introduced also add a layer of protection during charge. To complement the battery, Bluefin provides a custom charging station with power supply and a PC-based charge controller. Consider this example of the safety features in the charging process. If the firmware in the battery fails to recognize that the battery string has exceed an upper voltage limit, then hardware in the battery switches cut off the charge MOSFETs. If the charging computer fails to communicate with the battery, the watchdog shuts off the same switches and if all else fails, the computer can disable the charging power supply entirely.

Physically, the exterior of the battery is constructed in two parts. A hard, resilient engineering plastic shell that houses the bricks in a compensated oil environment combined with an aluminum lid. All of the electronic components are mounted to the lid which can be removed and replaced using nothing more than a screwdriver. While the top plate provides a heat sink for the power MOSFETs, it also locates the connectors and hardware that secure the battery to a specifically designed junction box. The exterior dimensions approximate 15" by 5.25" by 6.25" with a dry weight of 13.84kg or (30.51) lbs.

Bluefin also manufactures fully encapsulated battery packs that do not use compensating oil around the cells but just for the electronics. Full-encapsulation of cells and electronics makes for an even more rugged battery, and avoids any need to deal with compensating oil but, repairs to the integrated electronics are all but impossible, including dealing with a simple blown fuse.

For the oil-compensated batteries, Bluefin's team had to make provisions to store the excess oil required for compensation. Earlier prototype battery designs (Figure 2) used a simple polymer tube, extending from the oil-filled volume. While simple, the tube and its associated connector introduced a failure mode by including another path for water intrusion and the need for periodically inspecting the compensating fluid (and changing it as required).

To increase operational reliability, instead we have developed an integrated compensation device that maintains a near constant (above ambient) internal pressure in the battery as materials and small air voids compress or expand due to changes in external pressure. Similarly, we recognized that the pigtailed battery-cables (Figure 2) also made swapping



Figure 2. An older instantiation of the battery. Notice the plastic tube used for pressure-compensation and the need for pigtailed in the vehicle to mate with the battery connectors. Together, the pigtailed and tube occupied significant weight and space in the vehicle.

batteries into and out of the vehicle more time consuming than need be, as well as introducing more risks to the system. So we worked with Impulse Enterprises to create blind-mateable connectors for the battery. These significantly improve the system reliability.

The mating connectors are mounted on the low-profile junction box in the bottom of the AUV (Figure 3). All connections from the main electronics housing enter the oil-filled junction box. Rigidly mounted to the top of the junction box are guidepins and the mating connectors. To install the battery into the AUV, one removes the protective caps from all connectors (battery and junction box), and simply drops the replacement battery onto the guidepins exiting the junction box. The connectors then mate the battery's power and communications lines to the AUV.

The major advantages of this architecture are that:

- The plug and play batteries reduce difficulties designing, modeling and routing wet cables.
- The batteries are easy to remove and replace which enable a round-the-clock operations tempo.
- The junction box aids in wet wiring reduction while anchoring the batteries low in the vehicle for maximum CG/CB separation.
- The batteries present a uniform and flat surface that facilitates floatation design and placement.

Unlike connector pigtailed, these drop and play batteries



Figure 3. Rear section of the Bluefin 12" AUV. Three 1.5kWh batteries connect to the bottom mounted junction box to provide a uniform flat surface for floatation placement.

remove the need for cable management and prevents the simple but too common problems of cable snagging as cables are protected within the junction box.

IV. MANUFACTURING PROCESS

Cells arrive at our facility individually bar coded and individually tested by the manufacturer. The entire history of each cell up until it leaves the factory is available in the manufacturer's database.

Upon receipt, Bluefin re-tests each cell individually, recording several parameters such as capacity, charging characteristics, etc. The cells are then sorted and matched by the test results. All of the test results, as well as the sorting



Figure 4. One of the automated test stands used for electrically qualifying cells, quanta, and bricks. Note the fireproof cabinet that contains the cells under test. Over 22,000 cells have been tested using such systems. To date, Bluefin Robotics has produced 165 pressure-tolerant batteries, with capacities ranging from 1.0 to 3.6 kWh.

and matching, are recorded in our process database for each cell. Figure 4 shows one of Bluefin's automated test stands developed specifically for this task.

Matched cells are assembled into quanta, and each quanta undergoes a series of pressure cycles to test their mechanical stability. To date Bluefin has tested over 20,000 cells at 9000psi.

After pressure cycling, the quanta undergo electrical qualification. Specially designed electrical tests and experimentally derived acceptance criteria determine the integrity of the quanta. Once quanta pass the electrical qualification, they are assembled into the final battery, including implanting key safety sensors into the pack (e.g., temperature probes), and are mated with their electronics package.

The completed batteries undergo additional pressure cycling, with concurrent electrical testing. Having passed this final qualification, the battery is ready to be shipped and put to immediate use in an AUV.

Producing a safe, reliable, pressure-tolerant battery requires this level of investment in infrastructure, process development, and personnel training. Unless these processes are put in place, it is nearly impossible to produce batteries that will operate reliably in the extreme environments that these batteries experience in an AUV. One 1.5kWh battery contains 128 cells; each cell has to be perfect mechanically and electrically to ensure that the battery functions as intended.

Cell rejection is a certainty, this production process identifies any weak or out of tolerance components and removes them before the battery leaves Bluefin's plant. Every step is documented and captured into our proprietary battery

database. This means that the history of every cell in every battery is available if need be for supporting our customers.

V. DEVELOPMENT CHALLENGES

Batteries pack a large amount of energy into a compact object. As long as one controls the rate at which the energy is released, the battery is safe. However, there are a number of failure modes present in all cells, even when operating at 1 atm. The number of potential failure modes increases when the batteries are subject to repeated pressure cycling. Many of the new failure modes depend upon the materials used, and mechanical design of, the individual cells, their interconnections, the encapsulating material, and the final assembly. Additional failure modes can be introduced by the specific manufacturing methods used to create the cells and other components, and by the lot-to-lot (or item-to-item) variations found in any manufactured product.

The paramount concern of any team developing a new battery must be the safety of themselves, their co-workers, and their facility. Batteries will likely fail at various times in the development program therefore a full MTBF and FMEA need to be performed.

Any group beginning a program to develop a new pressure-tolerant battery needs to invest time and effort into two outside relationships (as well as pulling together an experienced engineering team internally). The first relationship is with the vendor selected to supply the cells to the program. Given the nature of the repeated mechanical stresses imposed on cells in a pressure-tolerant battery, it is likely that at least one change will be required in how the cells are manufactured if the battery is to be reliable and safe. The vendor has to be committed to the project, and willing to invest in changing their manufacturing parameters or processes to ensure success.

Second, the US Navy has significant experience in designing, testing, developing, and operating high-capacity batteries of all chemistries. We have been quite fortunate to draw upon the skills of the staff at NSWC-Carderock and NSWC-Crane. The NSWC team has been very generous with their deep knowledge of the many ways cells--and large assemblies of small cells--can fail. Any group beginning an effort to develop new batteries should talk with the NSWC battery team before embarking on their program, and cultivate that relationship throughout the development effort.

VI. SUMMARY

After a multi-year effort by an interdisciplinary engineering team, Bluefin Robotics has succeeded in creating a safe, reliable, high-performance, pressure-tolerant battery for use in AUVs (Figure 5). Our ultimate success has required a confluence of factors, including:

- A long-term program with sufficient support to invest in the testing and characterization infrastructure.
- An interdisciplinary team of skilled engineers, including personnel with many years experience designing

AUV energy systems and operating AUVs in environments ranging from the open ocean to Arctic ice camps.

- An industrial approach aimed at identifying pragmatic engineering solutions, rather than the broader, more fundamental approach of an academic effort.
- A near-obsession with safety in all aspects of the development program.
- Internal and external program managers who understood the need to do the job thoroughly.
- Partnering with a manufacturer of Li-polymer cells committed to the success of the effort.
- Good advice from those with experience in battery development.



Figure 5. Bluefin's pressure-tolerant battery design and development program has yielded a COTS battery system that is used across the Bluefin fleet of 9", 12" and 21" AUVs in addition to third party ROVs and other systems. This picture demonstrates the ease with which a user can replace the battery in the Bluefin 9" (Sealion) AUV. Concurrently swapping the data module removes almost all of the delay normally associated with back-to-back missions.

Serendipity also played a role in the success of this program through the partial failure of one cell under test, which (upon dissecting the cell) showed a subtle, un-anticipated failure mode. A fairly simple change in the manufacturing process for the cells seems to have resolved the issue, as not one of the many, many thousands of cells tested has failed under pressure since the change was made.

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